

The Development of Complex Adaptive Systems Based Decision Support Systems

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Introduction

The field of complex adaptive systems (CAS) is providing a powerful approach to simulate complex and highly dynamic problems. In CAS applications, software "agents" can be created to perform the role taken on by the real-world players. As an example, the human immune system can be modeled using a CAS approach in which software agents are created to take on the role of antibodies. In another example, ecosystems can be represented as a CAS problem with agents representing the species in the ecosystems, specific individuals, or a more aggregated communal forms like "hive" or "flock". CAS applications can also be used to model economic markets with agents being created to play the role of producers, distributors, or consumers.

In this paper, we describe work being conducted at the Argonne National Laboratory to develop CAS-based decision support systems to address a number of critical problems. We shall give a high level overview of what CAS agents are and how they work. We will summarize a number of ongoing programs at Argonne that are utilizing CAS analyses and then give examples from two specific programs.

What is an Agent?

At the most fundamental level, an agent is a software representation of a decision-making unit. Figure 1 shows a simple example of a software agent.

A software agent is given a set of decision rules that describe the data and conditions (i.e., thresholds) that determine when and what kind of decisive actions should be taken. The conditions and courses of action taken can vary as a result of the overall environmental conditions and various measures of performance that can be applied by the agent, or the larger environment, to assess how "well" the decisions are being made.

It is common to see the phrase "intelligent agents" in discussions of various agent applications. The reality is that agents are not "intelligent" from the cognitive awareness perspective, but they can be made quite "clever" by the sophistication of the reasoning algorithms that make up their decision making processes. As an example, a pricing agent could adjust prices for a given commodity based on a predefined relationship between supply and demand. However, the relationship could be adjusted to give higher prices if it is determined that (1) the commodity in question is critical and (2) consumers would accept the higher prices because there are no alternatives available.

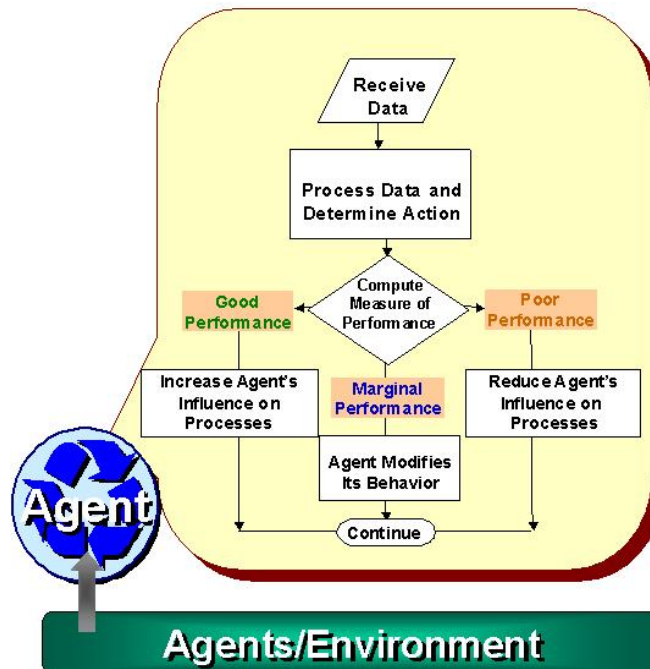


Figure 1. A schematic representation of how a generic agent can operate as a “decision-making” unit.

Agents are often characterized as being autonomous, semi-autonomous, or interacting with humans. Autonomous agents are those that can perform a given role without having a human in the loop. An example, could be an agent that automatically reorders stock items if the quantity on the shelf falls below a set level. A semi-autonomous agent is one that is given a set of conditions in which it can make decisions without human interaction, but is also given a range of conditions in which it must alert human operators and either inform them that the agent has performed a specified action or inform an operator of an impending condition that requires a human interaction and provides a recommended course of action. An example of the latter is the collision avoidance systems on modern aircraft that alerts the pilot that the plane is on a collision course and recommends an immediate course change.

In the military community, the majority of agent-based systems developed to support operators involve agents that interact with human operators as decision support tools that contribute to a course of action analysis. The agents can perform rapid analyses of complex situations and present one or more potential courses of action to take. But, the final decision will always be made by the human operator.

Complex Adaptive System Applications at Argonne

Argonne has a number of ongoing programs that involve the use of complex adaptive system simulations. These applications are addressing a number of problem domains, such as:

- **Electricity Markets** – The Electricity Market Complex Adaptive Systems (EMCAS) model is an agent-based model that simulates complex, realistic electric power markets.

- **Infrastructure Interdependencies** – CAS applications are being developed to study the interdependencies among natural gas, electric power, telecommunications, and petroleum networks.
- **Counter-drug Interdiction Strategy Analyses** – The Complex Adaptive System Countermeasures Analysis Dynamic Environment (CASCADE) program is being used to develop and analyze counter-drug strategies for interdicting drug trafficking.
- **Adaptive Communications Networks** – The Tactical Sensor and Ubiquitous Network Agent-Modeling Initiative (TSUNAMI) is addressing the U.S. Navy’s shift from platform-centric to network-centric warfare.
- **Terrorism** – The NetBreaker program is studying how to identify hidden networks based on partial information.

In the remainder of this paper, we will provide some examples of how CAS is being used in the EMCAS and CASCADE programs.

EMCAS

The Electricity Market Complex Adaptive Systems (EMCAS) model is an agent-based electricity market model written in Java and using RePast^{*}. EMCAS captures real-world behavioral patterns, such as those observed in the California electricity markets. EMCAS includes detailed power marketing and transmission infrastructure markets, as represented in Figure 2.

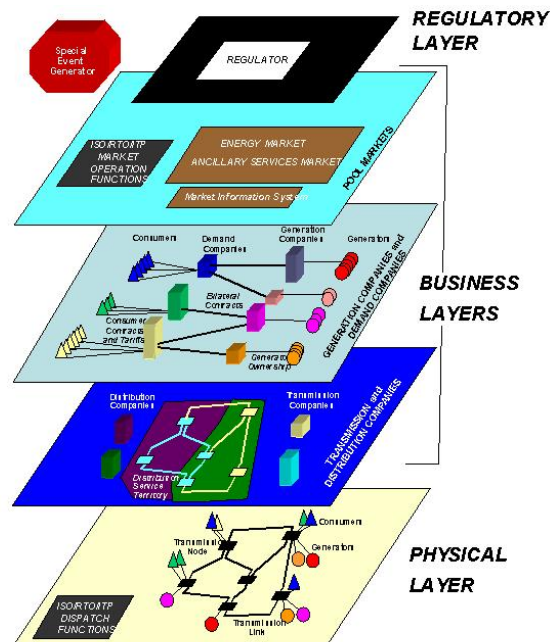


Figure 2. Schematic representation of the “layers” of functionality that can be represented in the Electricity Market Complex Adaptive Systems Model.

EMCAS agents take on the roles of individual market participants and are given the ability to make decisions based on various factors and different perspectives they can take on their part of

^{*}Repast is a software framework developed by the University of Chicago’s Social Science Research Computing for creating agent based simulations in Java. For more details, see <http://repast.sourceforge.net/index.ph>.

the market. For example, Figure 3 shows how an EMCAS generation company agent can look ahead and back in time as well as take a snapshot in time of the conditions facing it and competitors in order to make a decision.

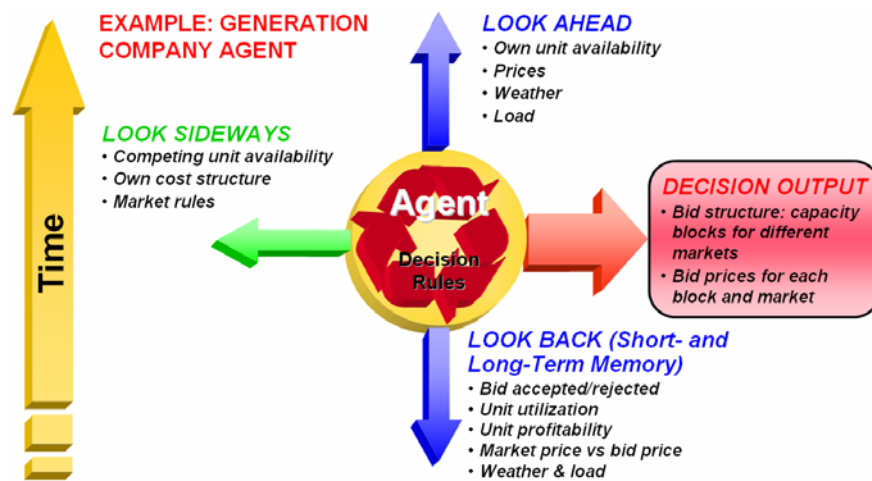


Figure 3. An example of how an EMCAS generation company agent can “look” in different temporal directions when making decisions.

All of the EMCAS agents work toward improving their own positions as they compete in various markets that are available to them, as represented in Figure 4. Individual generators and generation company agents can bid their generation capacity into any of the energy, bilateral, or ancillary services markets, subject to technical and physical constraints. Demand agents can satisfy their loads by bidding into the energy and bilateral markets. Demand agents can also bid the curtailment of interruptible loads into the ancillary services market as non-spinning (generators not spinning) reserve.

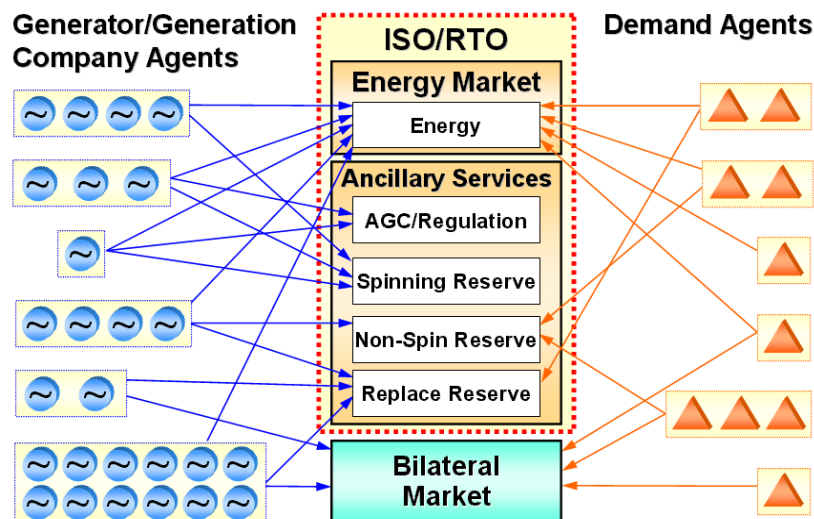
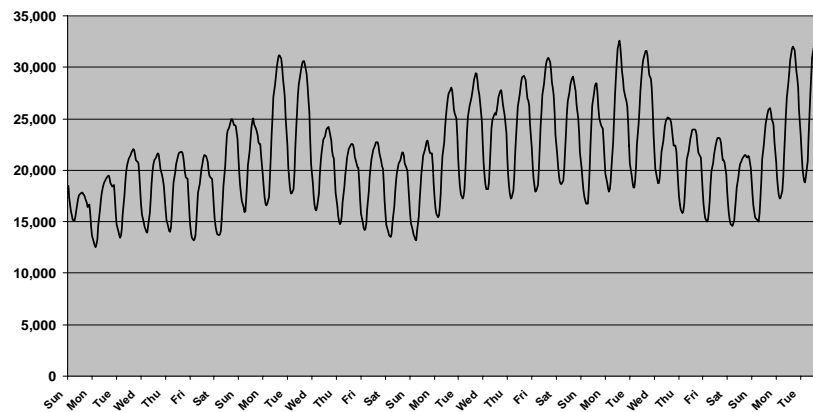


Figure 4. An example of how EMCAS agents can interact with different components of an energy market.

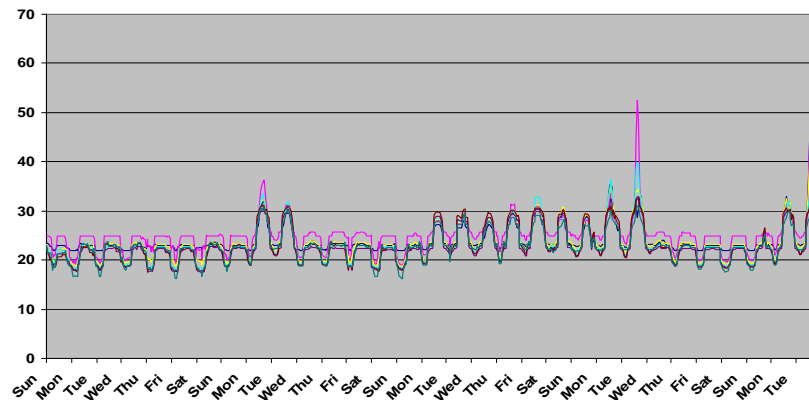
Finally, EMCAS agents can learn about their market and the forces that impact it, and make adjustments to their decision making processes. This is demonstrated in Figure 5, which shows (a.) the load served by a given market and (b.) the locational marginal price (LMP) in dollars per megawatt hour.

LMP is a tool for calculating the wholesale energy price for each location, or node, on a network grid. It can be used for scheduling power on a transmission system that recognizes potential transmission bottlenecks so that production schedules are consistent with real-time system limits. LMP is also used to allocate the use of limited transmission facilities to energy buyers and sellers in a non-discriminatory and efficient manner. Finally, LMP is used to make the best use of transmission and generation resources to serve loads and provide system reserves on a least-cost basis.

Typically, the LMP closely follows the load pattern. In the example shown in Figure 5, the LMPs increase at high load conditions. When a second and third peak in the load occurs, prices spike even higher as agents take advantage of the situation.



(a.) Load (MW) as a Function of Time



(b.) LMP (\$/MW hour)

Figure 5. An example of results from an EMCAS simulation in which agents “learned” about how the market reacted to a power outage and responded when a subsequent outage occurred.

(a.) The load as a function of time and (b.) the LMP as a function of time.

EMCAS is being used by the Illinois Commerce Commission to investigate the dangers posed by possible transmission constraints in Illinois in 2007. EMCAS agents are being used to simulate specific market participants, and the model will be used to determine the kinds and magnitudes of threats presented by possible transmission constraints.

CASCADE-CD

The Complex Adaptive System Countermeasures Analysis Dynamic Environment for Counter-Drug Applications (CASCADE-CD) was developed with support from the Joint Staff/J-8. CASCADE-CD was developed to aid drug analysts in deriving and justifying force structures and operational planning recommendations. It has also served as a “test bed” for the use of CAS techniques in “industrial strength” applications with the Department of Defense, such as developing new force structures and operational doctrines.

The focus within CASCADE-CD is on the drug “transit” zone for cocaine in the eastern Pacific, Caribbean, and Central America, with a limited representation of the “source” zone (e.g. Peru, Colombia, and Ecuador). The model explicitly represents the entire interdiction chain, including intelligence cueing, detection, sorting, monitoring, interception, visual identification, tracking, and the law enforcement “endgame.” The actual geography of the region is considered as well as the attendant geographic and geopolitical constraints, such as the requirements to get overflight approvals from the various countries in the region. Finally, the drug trafficker “enterprise” activities are treated as being embedded in the South American socioeconomic matrix.

The scope of the problem addressed by CASCADE-CD is exemplified in Figure 6. The left panel shows the primary smuggling routes taken by the cocaine traffickers before 1995. The “Blue” force that was created to interdict these routes was optimized for air interdictions and assumed the “Red” (i.e., drug-trafficker) forces would remain static. Between 1995 and 1998 (see the right panel), however, the Red forces became frustrated and adapted their forces to be able to accommodate ground and river routes. The Red route changes involved relatively low cost and rendered the air-dominated Blue force structure less effective.

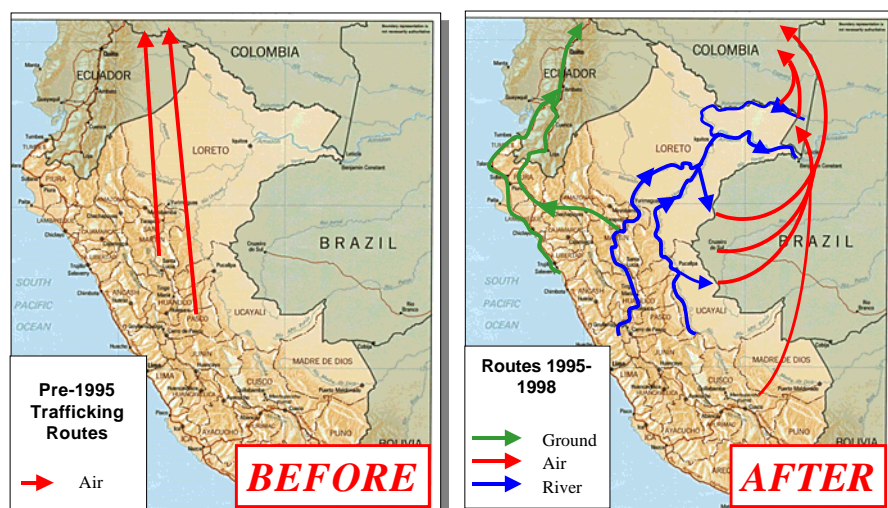


Figure 6. Historical scenario illustrating the scope of the problem being addressed by CASCADE-CD. Before 1995 (left panel), the Blue interdicting forces built a force structure in response to air-based drug trafficking routes. Between 1995 and 1998 (right panel), the Red trafficking forces adapted to the Blue force structure and began to favor ground and river routes.

On both the “Blue” and “Red” sides, adaptive behaviors are manifested in the agents at several scales and granularities, as represented in Figure 7. The figure shows different kinds of planning processes and steps that are taken by both the Blue and Red forces. The size of the different decision loops is meant to convey a feeling of where in the overall organizational structure a given process would occur. In some of the processes, an operations “stance” is created which is a set of dimensionless parameters that define an operations plan.

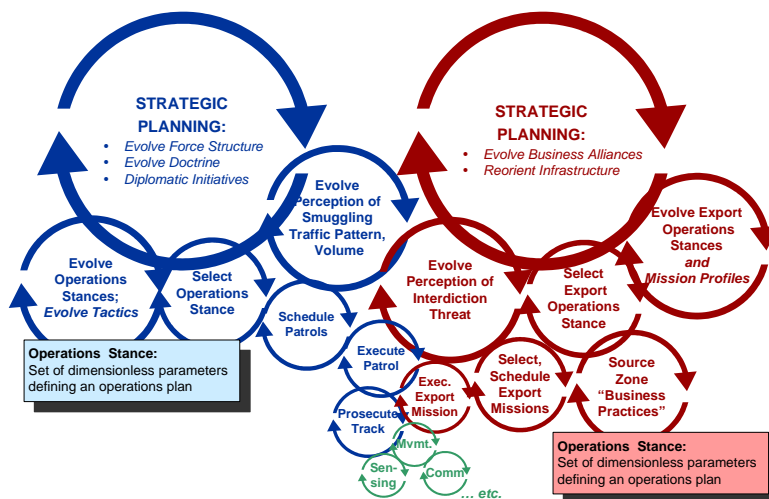


Figure 7. A representation of how the dynamic processes within CASCADE-CD are modeled at different scales and scope.

In developing the organizational structures for the Blue and Red forces, it was observed that while there is an organizational structure to the Red forces, it is not monolithic and hierarchical like that found in the Blue organization. Instead, the Red forces are an “ecology” of diverse organizations, like that notionally shown in Figure 8, and the modeled “cocaine trade” is the emergent behavior of “agents” working their own agendas.

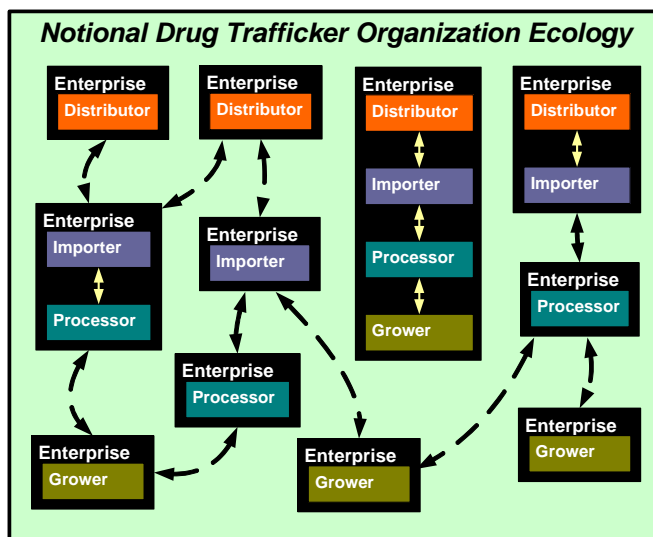


Figure 8. A notional drug trafficker organization ecology.

The counter drug operations that are performed are strongly asymmetric with respect to command, control, and communications in that the Blue forces tend to conduct theater operations under centralized control directed towards communications averse Red forces. In order to achieve success, an unusually high degree of coordination across diverse organizational boundaries (US military, participating nations, and law enforcement agencies) is required. This is especially true in dealing with air tracks, where timing is everything.

Genetic algorithms are used in CASCADE-CD to describe the behaviors of both the Blue and Red agents in terms of “operational stances” – a collection of parameters that address factors that are important to each side. Figure 9 describes the genetic algorithm factors used by the Blue and Red agents.

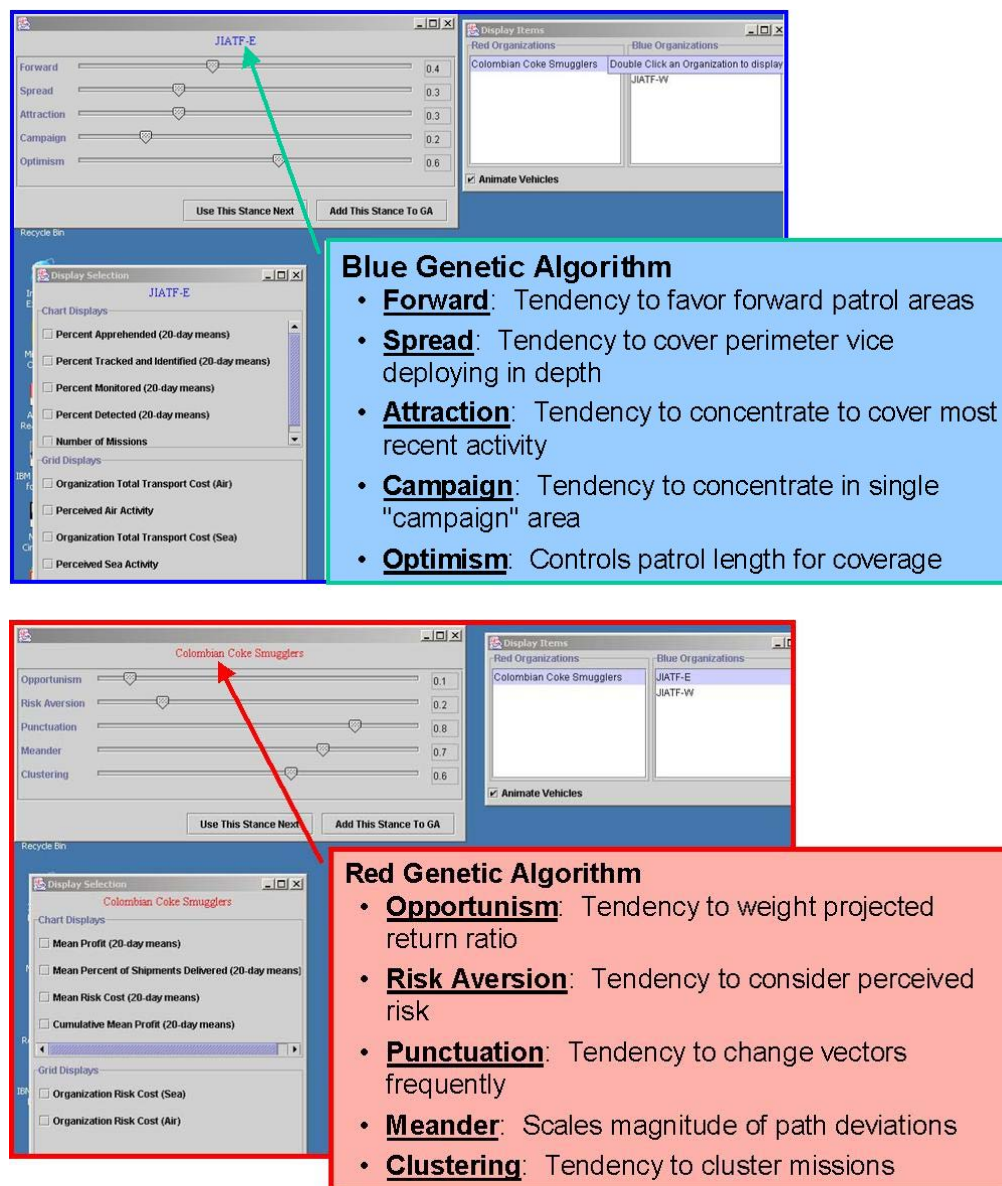


Figure 9. Description of the genetic algorithm factors used to describe the Blue force behaviors (upper panel) and the Red agent behaviors (lower panel).

During a simulation, a user can allow that agent's genetic algorithm to "evolve" better operational stances or the user can manually reset the value of each of the different factors using a simple slider bar. During a simulation, the behaviors of the agents change as they assess how well their plans are succeeding according to the behavioral conditions they have defined. For example, drug traffickers may vary their routes as they assess the "pros" and "cons" of the routes they are facing. A drug trafficker must weigh tradeoffs involved in selecting effective smuggling routes. A circuitous, meandering route to a destination is attractive to the smuggler in that it will make it harder for interdictor sensor systems, especially Doppler radar systems, to discriminate the flight from background air traffic, and will make continuous monitoring of the flight more difficult. On the other hand, the meandering route exposes the smuggler to interdiction for a longer period of time, and also requires more fuel than a beeline route to reach the same destination. CASCADE-CD explicitly models the sensitivity of a sensor system's performance to target aspect angle, radial velocity, and time since last vector change, so this rather subtle dynamic can be captured in the simulations.

CASCADE-CD provides a number of ways to review the results of a simulation. Figure 10 gives an example from an animation showing the interdiction of a P-3A EW aircraft maneuvering to monitor a drug trafficker flight. In this example, the drug trafficker's perceived air transport risk is shown as a color coded surface over the path being taken. In the example shown, the drug trafficker's organization believes the total transport costs over Costa Rica to be high due to its perceived significant risk of interdiction in a given area, and is therefore bypassing this area to the west.

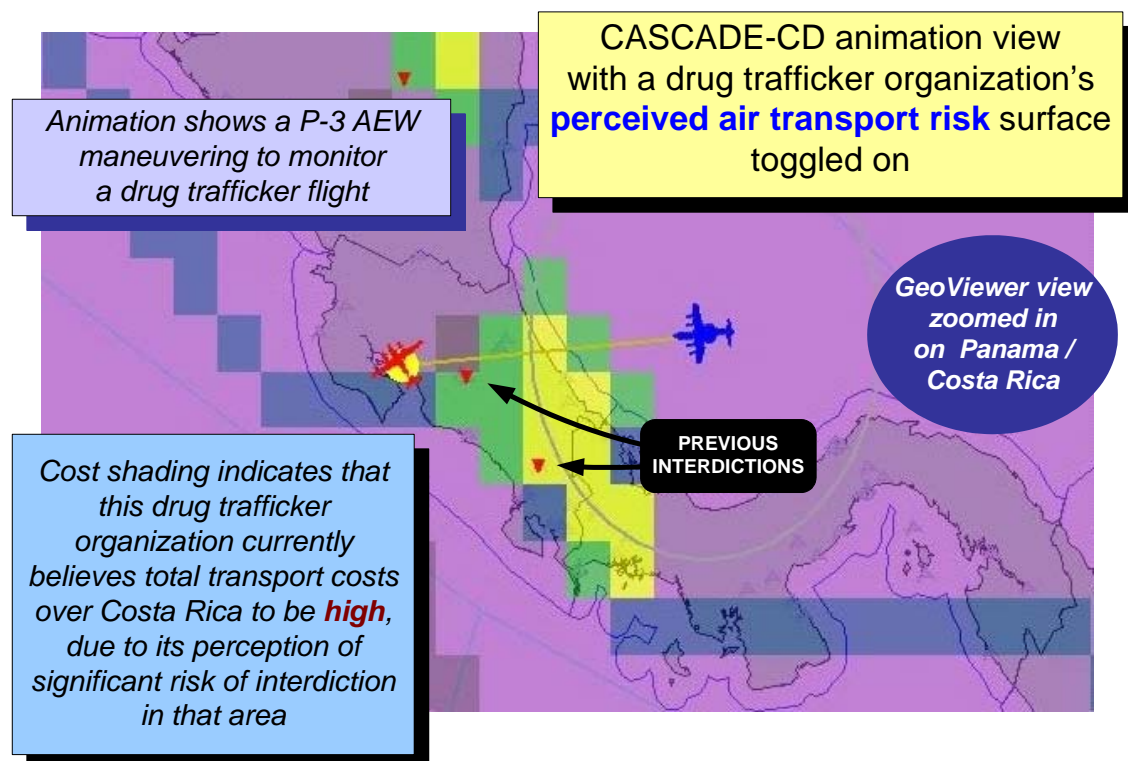


Figure 10. An example of a display from an animation view showing an interdiction between a Blue and Red asset.

Summary

The field of complex adaptive systems (CAS) is providing a powerful approach to simulate complex and highly dynamic problems. In CAS applications, software “agents” can be created to perform the role taken on by real-world players. Argonne National Laboratory has developed a number of CAS applications that are being used to study a variety of problems. In this paper, we gave an overview of these programs with specific examples of two programs.

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